TIMING OF DEGLACIAL ATLANTIC MERIDIONAL OVERTURNING VARIABILITY FROM A HIGH-RESOLUTION SEAWATER CADMIUM RECONSTRUCTION

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LIST OF ABBREVIATIONS

AAIW	Antarctic Intermediate Water
AMOC	Atlantic Meridional Overturning Circulation
Cd_w	seawater cadmium
EASM	East Asian Summer Monsoon
HS1	Heinrich Stadial one
ICP-MS	Inductively coupled plasma mass spectrometry
ITCZ	Intertropical Convergence Zone
LGM	Last Glacial Maximum
NADW	North Atlantic Deep Water
YD	Younger Dryas

SUMMARY

A new, high-resolution record of benthic seawater Cd (Cd_w) was generated from a Florida Straits-region sediment core. The record provides additional evidence for Cd_w below modern values at this location during the Younger Dryas and Heinrich Stadial 1-climatological periods associated with glacial melt. These results support the interpretation of changes in Cd_w in the region as indicative of the strength of Atlantic Meridional Overturning Circulation (AMOC). Lower Cd_w values imply a weaker AMOC, reducing the northward intrusion of higher-nutrient southern-sourced water. Comparison of this new Cd_w record with previously published neodymium isotope and $\delta^{18}O$ records from the same core shows synchronous transitions, further illustrating the connection between nutrient levels and AMOC strength in the Florida Straits. An increase in Cd_w near 16 ka implies a resumption of AMOC strength approximately midway through Heinrich Stadial 1, coincident with evidence of hydrological changes shown in several climate records.

1 Introduction

Atlantic meridional overturning circulation (AMOC) in the modern ocean transports heat from the tropics to the northern hemisphere. AMOC also transports tracers distinct to its component water masses based on where its waters were formed and/or for how long the water masses have traveled since formation. Because of its roles in deep water formation and heat transport, AMOC is cited as a global teleconnector of abrupt climate changes over the last glacial cycle. AMOC was likely greatly reduced, if not shut off, during the Last Glacial Maximum (LGM) around 20,000 years ago and at certain periods during deglaciation [*Boyle and Keigwin*, 1987],[*McManus et al.*, 2004]. Evidence for AMOC reduction has coincided with abrupt and short-lived (millennial-scaled) cold periods observed in the Northern Hemisphere. These cold periods are thought to be induced by large influxes of freshwater during glacial melt and ice sheet calving [*Broecker*, 1994]. Evidence for these events include data from circulation tracers and nutrient proxies, and are supported by modeling studies. However, uncertainty remains around the precise triggers, timing, and sequence of deglacial cold events.

Seawater cadmium (Cd_w) records over the Younger Dryas (YD, 12,700-11,500 years before present) North Atlantic cold period indicate that nutrient changes in the Florida Straits region are reflective of water mass redistribution in the upper branch of AMOC [*Came et al.*, 2008]. Cadmium has a nutrient-like profile that closely follows phosphorus, which varies distinctly in distribution by water mass, in the modern ocean [*Boyle et al.*, 1976]. Higher Cd_w is expected in the Florida Straits when AMOC is strong, as the enhanced circulation increases the northward influx of higher nutrient water transported from further south in the Atlantic. This study provides a higher resolution benthic Cd record than previously available for the region, complete for both HS1 and the YD.

A record of benthic foraminifera $\delta^{18}O$ in the Florida Straits shows that weaker AMOC in this region is reflected in the reduction of the density gradient across the basin during freshwater events [*Lynch-Stieglitz et al.*, 2011], [*Lynch-Stieglitz et al.*, 2014]. This new Cd record allows for direct comparison against other measurements of nutrient and circulation changes with datasets from other proxies in the same core. This allows us to distinguish between nutrient changes as evidence of remineralized nutrient changes, preformed nutrient changes, or water mass (circulation) changes.

2 Methods

We analyzed core KNR 166 2-26-JPC, recovered from 24°19.61′N, 83°15.14′W in the Florida Straits at 546m (intermediate water) depth. ^{14}C ages for the core were converted to calendar ages by the CALIB 7.1 calibration program and Marine09 marine reservoir calibration curve [*Reimer et al.*, 2009]. Calendar ages were then linearly interpolated. The core segment between 344 and 408 cm was excluded from the age model as the interval includes non-sequential radiocarbon dates and evidence of contourite deposition [*Lynch-Stieglitz et al.*, 2011]. Sedimentation rates ranged from ~14-300 cm/kyr, with an average of ~70 cm/kyr from LGM to present.

Cd/Ca ratios of the benthic foraminifera *Hoeglundina elegans* were used to calculate bottom water Cd (Cd_w). Cd_w is determined using the relationship

$$D_p = \frac{\left(\frac{Cd}{Ca}\right)\mathrm{foram}}{\left(\frac{Cd}{Ca}\right)\mathrm{water}}$$

where the average partition coefficient D_p between the foraminifera and seawater in *Hoeglundina* ≈1 for all depths [*Boyle et al.*, 1995]. Cd_w is estimated assuming a mean seawater Ca concentration of 0.01 mol/kg [*Boyle*, 1992].

Samples for analysis included 1-11 foraminifera tests each. Samples including at least 10 tests, or 9 tests > 500 µg, were divided into two vials for separate analyses. The tests were carefully cleaned using the methods of Boyle and Keigwin [*Boyle and Keigwin*, 1985] as modified by Boyle and Rosenthal [*Boyle and Rosenthal*, 1996]. Cd/Ca was measured using a Thermo Finnigan Element2 sector field ICP-MS using the trace metal detection methods delineated by Marchitto [*Marchitto*, 2006]. Values of Cd/Ca were excluded for sample sizes <1μg and for which other trace metal ratios in the sample were anomalously high (Fe/Ca or Al/Ca > 200 μmol mol^{-1}), which can indicate sample contamination. *Hoeglundina*'s aragonitic tests do not allow for magnesium carbonate overgrowths that can alter trace metal content [*Boyle et al.*, 1995].

a **b**

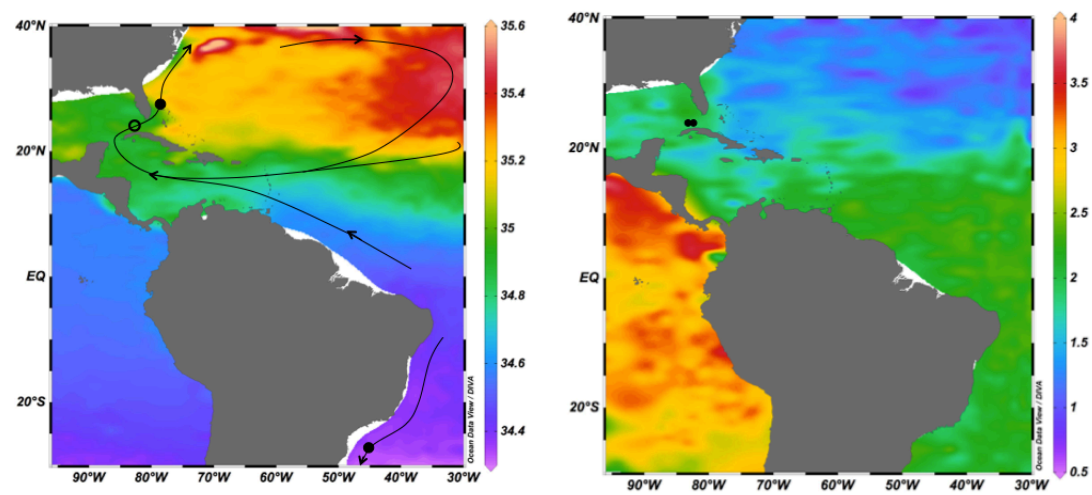


Figure 1. Core Locations. a, approximate location of Florida Straits cores, KNR 166 2-26-JPC, 24°19.61′N, 83°15.14′W, 546m (this study) and KNR 166-2-31JPC, 24°13′N, 83°18′W, 751m (open circle). Salinity (psu) gradients at potential density 27.3 kg m^{-3} [*Zweng et al*., 2013] : the isopycnal calculated for benthic waters at 26JPC. As waters circulate along constant density surfaces, salinity traces flow of different water masses through the Straits as indicated by arrows. OCE205-2-100GGC 26°04′N, 78°02′W, 1057m and KNR159-5-36GGC 27°31′S, 46°28′W, 1268m (closed circles) measure northern gyre and South Atlantic waters.
b. Modern PO_4 (μmol l^{-1}) [*Garcia et al.*, 2014] with 26JPC and 31JPC.

3 Results

Florida Straits seawater cadmium shows a clear increasing trend from the Last Glacial Maximum to the Holocene (Figs. 2, 3d). A transition from lower LGM levels to increased Cd_w occurs near 16 ka - about midway through the HS1. Cd_w reaches a maximum during the Bølling-Allerød North Atlantic warm period, near 13.8 ka. Cd_w then drops in a couple hundred years near the onset of the YD, remaining low before increasing to modern levels between 12 – 11.5 ka. That transition appears to be abrupt, but this is obscured by the previously noted gap in the record where sediments appear anomalously coarse, unevenly deposited, and were omitted from the age model and data.

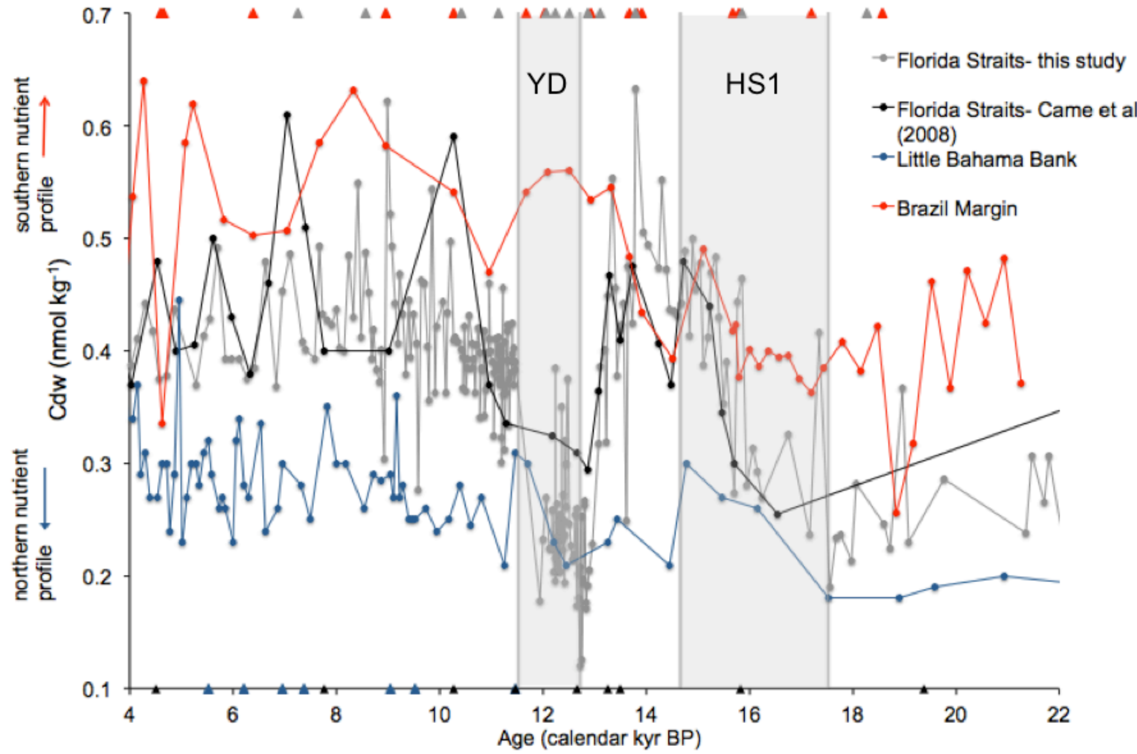


Figure 2. Benthic Cd_w of the Atlantic cores versus age. Gray, this study, all others [*Came et al.*, 2008]. Radiocarbon age control dates of the cores are indicated with triangles of corresponding colors. Gray bars indicate boundaries of the YD and HS1 North Atlantic cold periods.

These results are consistent with a Cd_w record generated from the 31 JPC core, located nearby in the Florida Straits at 24.22N, 83.30W, 751m [*Came et al.*, 2008]. Cd_w variations in this record were interpreted to indicate AMOC strength, based on a comparison between the Florida Straits record and two others with regionally distinct nutrient signatures. Cd_w in a core from the Little Bahama Bank reflects lower nutrient content in waters sourced in the North Atlantic and recirculated in the North Atlantic gyre. A core from the Brazil Margin has higher Cd_w values representative of its higher nutrient intermediate waters. Lower Cd_w values imply a weaker AMOC, reducing the northward intrusion of waters with nutrient levels reflecting both an incorporation of higher-nutrient, southern-sourced Antarctic Intermediate Water (AAIW) and reflecting remineralization in the tropics. Higher Cd_w in the Florida Straits implies greater compensation by southern water when North Atlantic Deep Water (NADW) production and overturning circulation is strong. Cd_w in both the northern and southern records compared in Came's study also reflect nutrient levels based on local productivity, but changes Cd_w in the Florida Straits over time reflect the relative inflows of North Atlantic gyre water and South Atlantic intermediate water. For both the 26 and 31 JPC records, intermediate Florida Straits water appeared predominated by a northern circulating water mass during the YD and more by southern influxes during the Bølling-Allerød (Figure 2). Similarly, based on the JPC 26 record, we are able to interpret the lower Cd_w during the first half of HS1 as indicating a reduced AMOC regime.

4 Discussion

4.1 Co-located proxy comparisons

Florida Straits neodymium isotope records provide further insights on the timing of these water mass transitions. Nd isotope ratios trace water masses independently of biological processes. Today, the ratios for the water masses sourced in the North Atlantic are near ε_{Nd} = -13.5 [*Piepgras and Wasserburg*, 1980] [*Piepgras and Wasserburg*, 1987], and higher, -6 to -9, for waters sourced in the Southern Ocean [*Jeandel*, 1993]. The difference is based on the inputs of older weathered continental material into the Atlantic or newer volcanic weathered material in the Pacific, a mixture of which comprises Southern Ocean water. Comparing the 26 JPC Cd_w record with ε_{Nd} from the same core (Fig. 3c) [*Xie et al.*, 2012], transitions in the deglacial cold periods are in agreement. Authigenic ε_{Nd} transitions from more northern-like to more southern-like values between ~16 ka into the Bølling-Allerød and a decline again into more northern values at the YD. This suggests AMOC weakened such that AAIW intrusion declined during HS1 and YD, and AMOC recovered during the Bølling-Allerød. Similar transitions exist for ε_{Nd} in the neighboring 31 JPC core [*Came et al.*, 2008]. While the ε_{Nd} records do not agree with those from a deeper core in the Tobago Basin [*Pahnke et al.*, 2008], same-core consistency between ε_{Nd} and Cd_w supports the conclusion of Xie et al. [2012] that the Tobago Basin core, at 1330 m and below the modern depth of AAIW at the site, may not record the presence or absence of AAIW in the North Atlantic.

$\delta^{18}O$ in the Florida Straits also records the strength of Atlantic overturning circulation. It was determined that there the change in the density gradient of waters across the basin represents the strength of overturning circulation. [*Lynch-Stieglitz et al.*, 1999]. The gradient increases when a stronger geostrophic current increases vertical shear. When flow weakens, the gradient declines as isopycnals across the Florida-side and the Bahamas-side of the Straits flatten. For 26 JPC, this is apparent as a decrease in $\delta^{18}O$ over the YD and the HS1, indicating temperature increases at the core location [*Lynch-Stieglitz et al.*, 2011; 2014]. A comparison of the $\delta^{18}O$ transitions concurrent with those of Cd_w (Fig. 3a) provides further validation for the link between AMOC strength and local water mass changes. The Cd_w record also bolsters a similar $\delta^{18}O$ interpretation for HS1 as for the YD, despite the lack of an interpretable Bahamas-side record during the Heinrich Stadial.

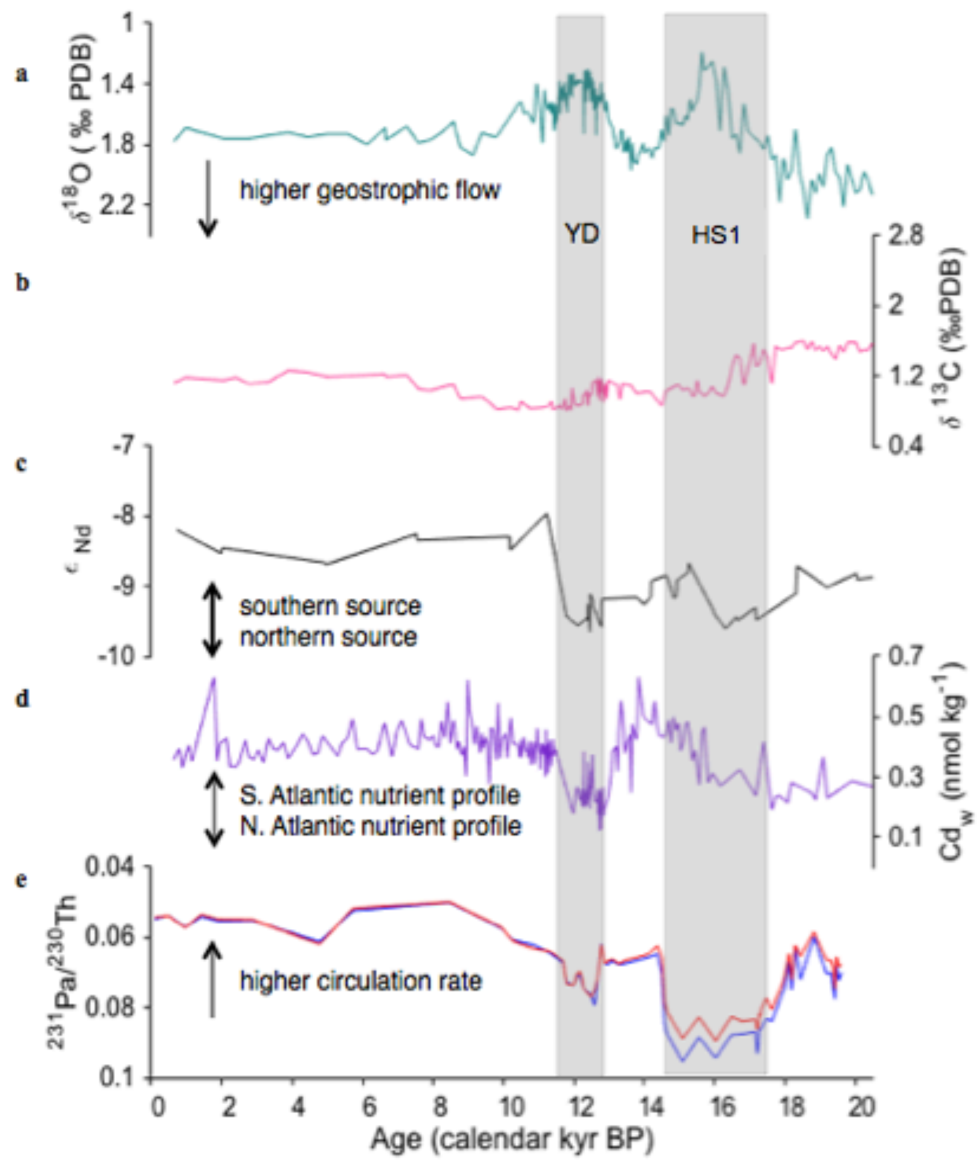


Figure 3. Tracers of North Atlantic circulation over deglaciation. From Florida Straits (26 JPC) a, ice volume-corrected $\delta^{18}O$ [*Lynch-Stieglitz et al.*, 2014], b, $\delta^{13}C$ (this study), c, authigenic ε_{Nd} [*Xie et al.*, 2012], d, Cd_w (this study), e, $^{231}Pa/^{230}Th$ from the Bermuda Rise [*McManus et al.*, 2004].

All these findings lend support to reading the deglacial nutrient changes in the Florida Straits as predominately influenced by AMOC's strength, which determines the proportions of water masses that dominate the region. The results also contradict a view of North Atlantic nutrient changes based on accumulation effects in an AMOC-collapsed condition. A model study [*Schmittner and Lund*, 2015] finds that a shutoff of AMOC increases North Atlantic deepwater residence time. The authors conclude that $\delta^{13}C$ in intermediate and benthic waters drop when AMOC declines, both as weakened deepwater production reduces the injection of higher $\delta^{13}C$ waters, and also as respired organic matter low in $\delta^{13}C$ accumulates. However, in the Florida Straits, changes in $\delta^{13}C$ are inconsistent with AMOC variability: expected gains in $\delta^{13}C$ as AMOC recovers are not seen (Figure 3). The same-core ε_{Nd} circulation tracer allows for comparison with the nutrient water mass tracers $\delta^{13}C$ and Cd_w. Doing so reveals consistent transitions between ε_{Nd} and Cd_w for both deglacial cold periods, suggesting that at least part of the Cd_w nutrient signal is reflective of changes in the proportions of southern-sourced water masses. The $\delta^{13}C$ in this region may be reflecting effects other than circulation and in-situ productivity, namely, air-sea exchange.

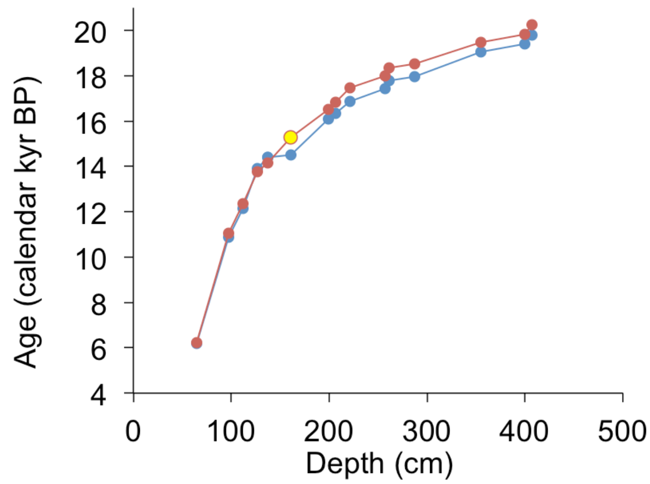
4.2 Pa/Th comparison

McManus et al [*McManus et al.*, 2004] used the $^{231}Pa/^{230}Th$ quasi-conservative water mass tracer to estimate the rates of overturning circulation decline over deglaciation. In seawater the ratio of production of these isotopes is 0.093, calculated from a constant rate of production from alpha decay of oceanic ^{235}U and ^{234}U, respectively, which are approximately uniformly distributed. Both particles are scavenged from the water column before burial (^{230}Th at a faster rate) [*Yu et al.*, 1996],[*Chen et al.*, 1986]. Therefore, higher $^{231}Pa/^{230}Th$ in the Bermuda Rise implies weaker AMOC, with a ratio of 0.093 indicating a complete shutdown.

Data from a core from the Bermuda Rise region [*McManus et al.*, 2004] showed evidence of AMOC decline spanning HS1 and YD. While the shorter transitions in and out of the YD cold period are similarly timed in the $^{231}Pa/^{230}Th$ and the Florida Straits Cd_w record, the HS1 $^{231}Pa/^{230}Th$ increase spans 17.5-15ka. In that record, AMOC recovery at the end of H1 appears to occur rather rapidly, over about 500 years from15-14.5ka. By contrast, the Florida Straits Cd_w record implies a more gradual recovery beginning near 15.7ka (Fig 3e).

A simple explanation for the difference in timing and rate of AMOC changes out of HS1 could be found in the age modeling of the cores. For GGC5 [*McManus et al.*, 2004], age constraints are provided by sixteen reservoir-corrected radiocarbon dates from three foraminifera species. One core depth point within the age model curve appears to be anomalously young. Upon reexamination of the age model, replacing the anomalously young point with a “dummy” older date estimated to better fit the overall trend of the core (Fig. 4a) realigns AMOC recovery such that it is evident in the $^{231}Pa/^{230}Th$ record earlier and progresses more gradually, and in sync with that of the Cd_w record. This result is seen with a shift of a single point of the radiocarbon age, and cannot be achieved by simply updating the calibration model used for converting ^{14}C ages to calendar years (Fig 4b). This hypothesis regarding the timing of AMOC change in the GGC5 core should be tested by additional radiocarbon dating.

a



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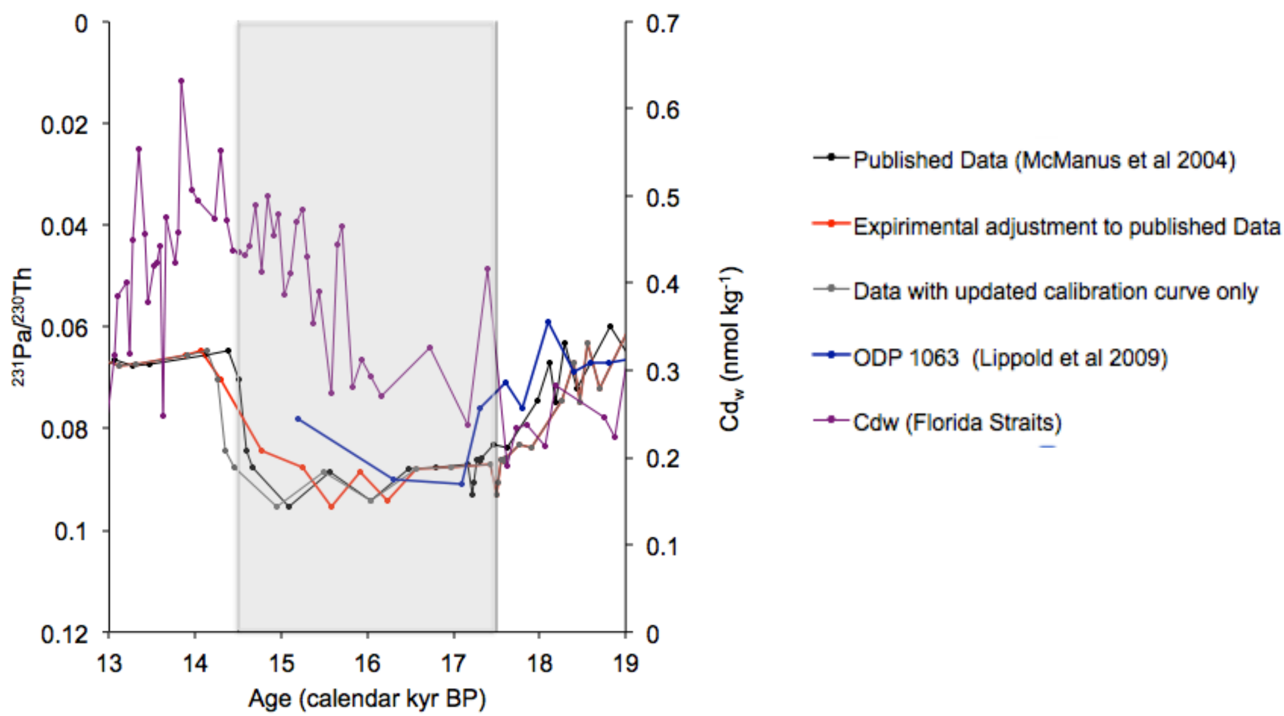

Figure 4. Experimental revisions to GGC5 (Bermuda Rise) age model. a, age vs. depth for published [*McManus et al.*, 2004] age model (blue) and a revision based on updated radiocarbon calibration [*Reimer et al.*, 2009] (red) and a refitted date for 161 cm (yellow point). b, Comparison between the published data and those with experimental adjustments made to the age model. Florida Cd_w shown in purple. Gray bar indicates HS1 interval.

Lippold et al (2009) [*Lippold et al.*, 2009] provide an additional $^{231}Pa/^{230}Th$-based record of overturning from a nearby core in the Bermuda Rise (ODP 1063, 33 41' N, 57 37'W, 4584m). This core, which also shows increases in $^{231}Pa/^{230}Th$ over earlier Heinrich Stadials, tracks closely to McManus et al's record over Heinrich Stadial 1. Unfortunately, the ODP 1063 record terminates at 15.2 ka. However there is a steep decline in $^{231}Pa/^{230}Th$ from 16.3 ka to 15.2 ka. While the lower resolution of ODP 1063 over HS1 complicates direct comparison, the fidelity between the cores leading from LGM to HS1 supports the idea that ODP 1063 record is faithfully recording AMOC circulation, and the earlier AMOC resumption seen around 16 ka evident in 26 JPC, 31 JPC, and possibly ODP 1063 differs from GGC5 because of erroneous dating in GGC5 around that time.

Consulting other North Atlantic $^{231}Pa/^{230}Th$ records fails to resolve the issue. In Gherardi et al's [*Gherardi et al.*, 2009] analysis of six North Atlantic $^{231}Pa/^{230}Th$ records (including GGC5), two cores above 3km do not show an AMOC decline over HS1. Two other, deeper cores whose sedimentary flux rate permit a circulation-signal interpretation of $^{231}Pa/^{230}Th$ over H1 show transitions more consistent with a later AMOC recovery. It is clear that additional constraining proxies in the region will be necessary to better understand the variance in circulation changes across the region.

4.3 Two-phase Heinrich Stadial One

The change of inflection of Cd_w in the Florida Straits record near 16 ka implies a mid-HS1 AMOC recovery. If AMOC resumed before the end of HS1, it should also be apparent in climate records. A strong AMOC results in a stronger temperature gradient between hemispheres, helping fuel monsoon systems [*Parsons et al.*, 2014]. Furthermore, reduction in AMOC and reduction of the northward transport of heat and moisture has been linked to southward shifts of the Intertropical Convergence Zone (ITCZ) [*Chiang et al.*, 2003], [*Deplazes et al.*, 2013].

An abrupt weakening of the East Asian Summer Monsoon (EASM) at 16.1 ka is inferred from Chinese speleothem records [*Wang et al.*, 2001], [*Zhang et al.*, 2014]. The Hulu Cave record shows evidence of EASM weakening during six Heinrich Stadials, which Wang et al (2001) link to North Atlantic climate change. If EASM strength is tied to AMOC, as AMOC weakens, so should EASM, via atmospheric and oceanic teleconnections. This is apparent in the Hulu Cave record during HS1. While the largest and most rapid shift back towards stronger monsoon values does not occur until 14.6ka, the beginning of the Bølling-Allerød, the 16.1 nadir in monsoon strength may be an inflection point whereafter EASM strength gradually increases.

Rodríeguez-Sanz et al's (2013) [*Rodríguez Sanz et al.*, 2013] study of the San Làzaro Basin near the California Margin shows that YD and HS1 are locally marked by high surface water $\delta^{18}O$. The saltier conditions observed in those periods are ascribed to a weakening California Current, which prevented the advection of colder fresher water as observed in the Holocene. The authors link the weakening current to the southward shift of the ITCZ and the North Pacific High. Also observed is a distinct two-phase structure to the local expression of HS1. There is a sharp transition from saltier to fresher conditions in the San Làzaro Basin starting at 16.2 +/- 0.8 ka, consistent with the timing of the ITCZ maximum southern displacement recorded in Hulu Cave and with resumption of AMOC recorded in the Florida Straits near 15.7 ka.

Broecker et al [*Broecker et al.*, 2009] and others suggest attributing mid-HS1 hydrological changes to a second North Atlantic ice rafting event dated near 16 ka (H1a, the other H1-related event is H1b, at 17.5 ka [*Bard et al.*, 2000]). These authors note the dilemma that this poses- if a glacial discharge induced the initial hydrological shifts at the start of HS1, why should an additional ice rafting event mark the inflection point after which Holocene-like conditions initiate? Broecker et al. (2009) note the lack of evidence for AMOC change near 16 ka in proposing other sources of thermal reorganization. However, the Florida Straits Cd_w record provides evidence for a recovery of AMOC strength beginning near 15.7 ka, and before the HS1 period, as expressed in ice core $\delta^{18}O$ [*NGRIP members*, 2004], North Atlantic $^{231}Pa/^{230}Th$ [*McManus et al.*, 2004], and other records, is terminated. The start of AMOC strengthening does not resolve the two-phase HS1 dilemma, and the precise relationship between the mid HS1 recovery and the H1a discharge is unresolved. Clearly, further investigation into the timing and locations of deglacial freshwater hosing, AMOC variability and related climate impacts are necessary. To that end, this Cd_w record provides compelling evidence for a mid-HS1 AMOC recovery against which other proxy measurements over HS1 can be compared.

5 Conclusions

The new benthic seawater cadmium record provides a high-resolution record of circulation changes over the Florida Straits. Multiple proxy records from the same core support the interpretation of periods of diminished Cd_w during Heinrich Stadial 1 and the Younger Dryas periods as indicative of reduced overturning circulation in the North Atlantic. The record provides a shows a resumption of AMOC strength near 16 ka, which is coincident with hydrological changes in several records. This timing supports evidence for a multi-phased Heinrich Event during HS1 that imparted climatological change influenced by changes in AMOC strength. This record provides a new means of comparison between AMOC variations and other records of abrupt climate change.

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